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# Luminous efficiency enhancement of white light-emitting diodes by using a hybrid phosphor structure

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**Abstract.** This paper presents a “hybrid” structure for the coating of yellow YAG:Ce<sup>3+</sup> phosphor on blue GaN-based light-emitting diodes (LEDs). The luminous efficiency of the hybrid phosphor structure improved by 5.9% and 11.7%, compared with the conventional remote and conformal phosphor structures, respectively, because of the increased intensity of the yellow component. The hybrid structure also has an advantage in the phosphor usage reduction for the LEDs. Furthermore, the electric intensity of the hybrid phosphor structure was calculated for various thicknesses by conducting TFCalc32 simulation, and the enhanced utilization of blue rays was verified. Finally, the experimental results were consistent with the simulation results performed using the Monte-Carlo method. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JPE.5.057603](https://doi.org/10.1117/1.JPE.5.057603)]

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## 1 Introduction

Recently, the development of white light-emitting diodes (WLEDs) has become the latest step toward a revolution in lighting technology.<sup>1-3</sup> The advantage of WLEDs is a small size, high energy efficiency, low cost, and color stability, which improve lighting applications including liquid crystal displays backlighting in mobile phones and other handheld devices, dashboard lighting, and the headlights used in automobiles.<sup>4,5</sup> Currently, phosphor-converted white light-emitting diodes (pcWLEDs), in which a blue chip and yellow-emitting phosphors are combined, are the most popular packaging structure used to produce white light.<sup>6</sup> Regarding GaN-based LED chips, the progress in white LEDs is strongly driven by the advances in high-efficiency GaN-based LEDs that emit light in the visible spectral regime. These GaN-based LEDs are used as high-power pump excitation sources in pcWLEDs. Recent studies have substantially improved GaN-based LEDs by using new types of active regions featuring reduced charge separation,<sup>7-9</sup> nano/microphtonics structures,<sup>10,11</sup> growth and substrate technologies,<sup>12-15</sup> and barrier engineering.<sup>16-18</sup> Thus, the availability of high-efficiency nitride LEDs has enabled the practical implementation of pcWLEDs.

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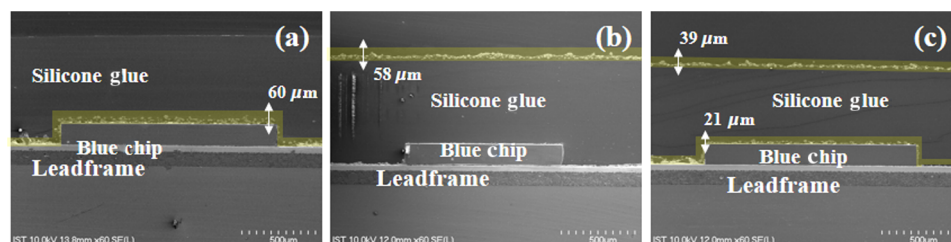
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To fabricate the pcWLEDs configurations, the yellow-emitting phosphor powders are mixed with transparent encapsulated resin and then dispersed in a cup reflector or directly coated on the LED chip surface. Although this direct dispensing method enables the thickness of the phosphor layer to be easily controlled and reduces much of the cost, it does not produce high-quality WLEDs.<sup>19</sup> Thus, the conformal phosphor structure can be used as an alternative. This method is used to uniformly distribute colors, causing angular homogeneity of the correlated color temperature (CCT).<sup>20</sup> However, the disadvantage of a conformal phosphor structure is the backscattering effect, in which more than half of the light is backscattered to the absorptive LED chip.<sup>21</sup> To alleviate this backscattering problem, the phosphor layer can be separated from the chip to suppress the reabsorption. Thus, various phosphor structures, such as the remote phosphor structure, have been designed to address this problem.<sup>22,23</sup> In this structure, the concave encapsulant surface causes the phosphor thickness to become nonuniform during the fabrication of the remote phosphor structure. A nonuniform phosphor is suggested to cause yellow rings after activating the device. Therefore, the patterned remote phosphor structure and  $ZrO_2$ -type package have been employed to improve the uniformity of the angular-dependent CCT.<sup>24,25</sup>

In this study, a hybrid phosphor structure was employed in an array of blue LED chips on board (COB) to increase light output compared with the conventional remote and conformal phosphor structures. Compared with the conventional package leadframe, the advantages of a COB package are its heat dissipation and thinness, which make the COB package suitable for use in high-power lighting sources.<sup>26,27</sup> The experimental results indicated that a hybrid phosphor structure yields a high intensity of yellow components because the trap of the incident pumping blue rays inside the structure increases the absorption probability of the phosphor layer and delivers additional yellow rays. The hybrid structure also has an advantage in the phosphor usage reduction for the white LEDs. The hybrid structure saves more than 17% and 37% in phosphor usage, compare to the remote and conformal structures at color temperature 5300 K. Moreover, a TFCalc32 simulation revealed that the power intensity between the phosphor layers is enhanced when using a hybrid structure.

## 2 Experiment

In this study, hybrid phosphor structures were fabricated using the pulsed spray coating (PSC) method,<sup>18</sup> which is used to spray the phosphor slurry in uniform layers and easily control the CCT. Moreover, this method is convenient, does not cause chemical pollution, and is suitable for fabricating planar illumination systems with large areas.<sup>28</sup> The phosphor powder used in this experiment was  $YAG:Ce^{3+}$  with a particle size of  $13\ \mu\text{m}$ . The LED leadframe size was  $22\ \text{mm} \times 25\ \text{mm}$ , and the chip size and thickness were  $45\ \text{mil}^2$  and  $150\ \mu\text{m}$ , respectively. Four GaN-based blue LEDs with a peak emission wavelength of approximately 450 nm were bonded on silver glue with gold wire to the bond pad. A SEM cross-sectional view of a hybrid phosphor structure is shown in Fig. 1. The samples, which featured hybrid phosphor structures, were fabricated using the following steps: (1) the PSC method was employed in spraying phosphor on the chip to form the bottom phosphor layer; (2) the transparent silicone binder was dispensed into the lead frame and cured in an oven at a temperature of  $150^\circ\text{C}$  for 1.5 h; and (3) the phosphor was sprayed on the top of the silicone binder layer to form the hybrid phosphor structure at the same total amount of phosphor. In this experiment, the total density of the phosphor was set as  $6\ \text{mg}/\text{cm}^2$  for all of the samples, and the density of the phosphor was

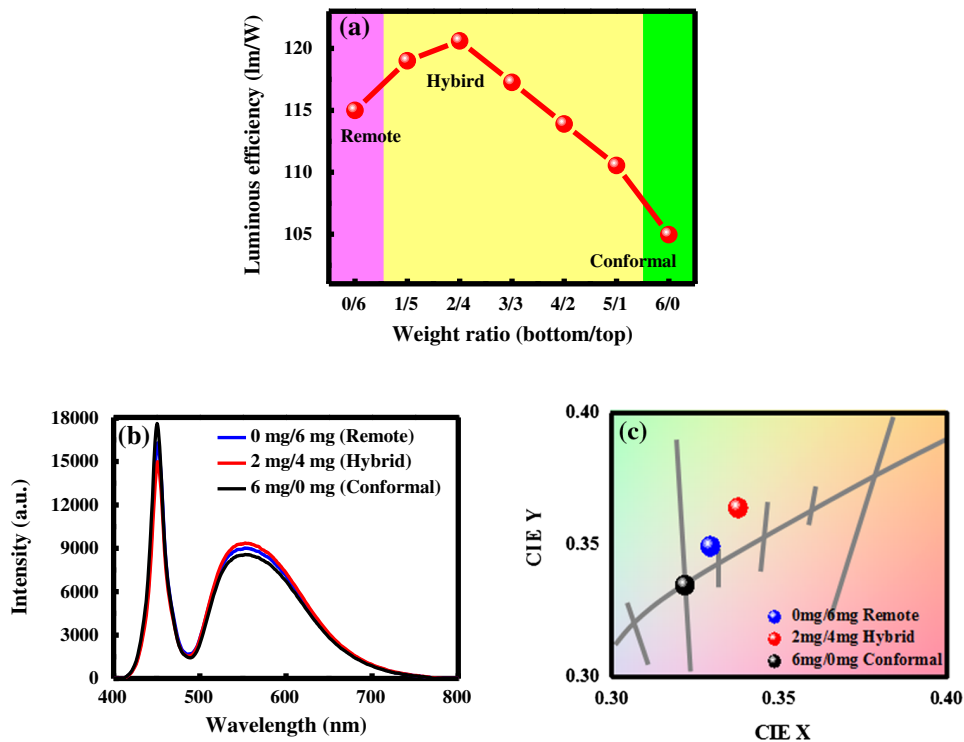


**Fig. 1** SEM cross-sectional view of (a) conformal, (b) remote, and (c) hybrid phosphor structures.

approximately  $1 \text{ mg/cm}^2$  from one spray coating step. To understand the performance of the devices and optimize the luminous efficiency, the top and bottom phosphor layers of the hybrid phosphor structure were fabricated in various thicknesses but with the same total amount of phosphor. For convenience, we use a simple weight ratio such as  $1 \text{ mg}/5 \text{ mg}$  (bottom/top) to replace the  $1 \text{ mg/cm}^2$  in the bottom phosphor layer and  $5 \text{ mg/cm}^2$  in the top phosphor layer. To compare the hybrid phosphor structure with the conventional phosphor structure, the remote and conformal phosphor structures were fabricated with the same amount of phosphor, and the weight ratio of  $0 \text{ mg}/6 \text{ mg}$  (bottom/top) and  $6 \text{ mg}/0 \text{ mg}$  (bottom/top) represented the conventional remote and conformal phosphor structures, respectively. In this study, every data point is the average value of five LEDs for the proposed structure. The LED devices were measured under continuous-wave conditions at room temperature and the light output was collected by an integration sphere. This integration sphere was 30 cm in diameter. The influence of external impact on the measurement is much smaller in a closed integration sphere system.

### 3 Results and Discussion

As shown in Fig. 2(a), the bottom and top phosphor layers of the hybrid structure were fabricated in various ratios to optimize the luminous efficiency at a forward current of 700 mA. The experimental results indicated that the optimal weight ratio of the bottom to top phosphor layers is  $2 \text{ mg}/4 \text{ mg}$  (bottom/top), which produces a higher luminous efficiency compared with that of conventional structures. Specifically, the hybrid structure exhibited 5.1% and 14.9% improvements in luminous efficiency compared with the remote and the conformal phosphor structures, respectively. Figures 2(b) and 2(c) show the emission spectra and CIE 1931 diagram of the hybrid structure, conventional remote structure, and conformal phosphor structure. The hybrid phosphor structure produced a higher intensity in the yellow component than did the remote and conformal phosphor structures, indicating that this structure can be applied for improving the



**Fig. 2** (a) The luminous efficiency of the different ratios of phosphor layers in hybrid phosphor structure. (b) The emission spectra of the remote phosphor structure, the conformal phosphor structure, and the hybrid phosphor structure driven at current of 700 mA. (c) The CIE 1931 chromatic diagram of remote, conformal, and hybrid phosphor structures.

luminous efficiency of LED structures. Conversely, the hybrid phosphor structure exhibited lower intensity in blue rays than the remote and conformal structures did, because the utilization of the blue light causes an increase in the absorption probability of phosphor and delivers additional yellow rays.

To determine the optical characteristics of the remote, conformal, and hybrid phosphor structures when driven at currents from 100 to 1000 mA, the current-dependent luminous efficiency and luminous flux were analyzed, as shown in Fig. 3. The luminous efficiencies of the remote, conformal, and hybrid phosphor structures were 117, 111, and 124 lm/W, respectively, at a driving current of 700 mA. The output luminous efficiency of the hybrid phosphor structure was observed to increase by 5.9% and 11.7% compared with the conventional remote and conformal phosphor structures, respectively. When applying a high injection current, the enhancement of the luminous efficiency showed a stable value, which could have been attributed to the enhanced use of emissions by both blue and yellow rays in the hybrid phosphor structure.

Figure 4 shows the measured CCT for various ratios of the bottom to top phosphor layers of the hybrid structure. Regarding the conventional, remote, and conformal phosphor structures, when blue rays excited the phosphor, yellow rays were emitted in all directions. A large proportion of downward rays, including blue and yellow rays, were transmitted back to the blue LED chip, causing the utilization of blue rays to be low. The conventional remote and conformal phosphor structures clearly exhibited higher CCTs than the hybrid structure did. The CCT of the hybrid phosphor structure composed of a bottom-to-top phosphor-layer weight ratio of 2 mg/4 mg was located at 5300 K. Confining the blue rays in the silicone layer can improve its utilization by increasing the probability of phosphor excitation. It is also worth noting that the optimized hybrid phosphor (2 mg/4 mg) structure saved phosphor usage. In Table 1, we listed

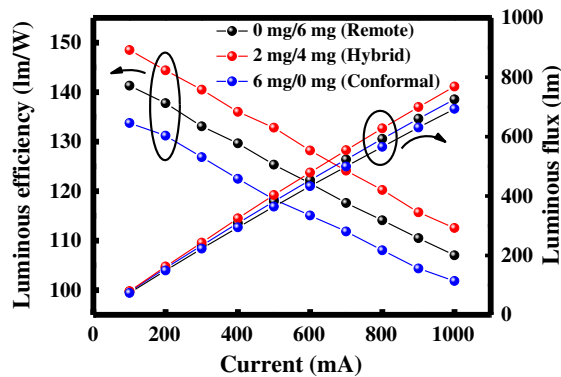


Fig. 3 Luminous efficiency and luminous flux of the remote, conformal, and hybrid phosphor structures with a ratio of 2/4 driven at currents from 100 to 1000 mA.

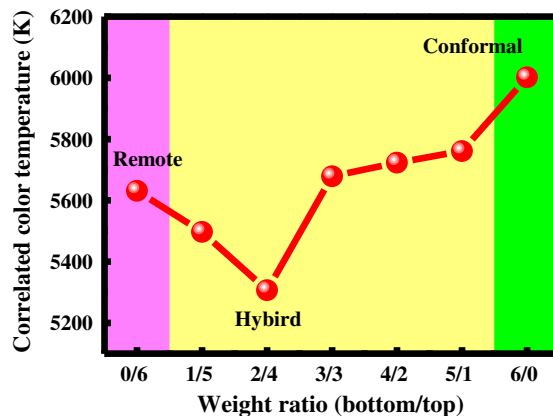


Fig. 4 The correlated color temperature (CCT) of the different ratios of phosphor layers in hybrid phosphor structure.

**Table 1** Phosphor usage in three LED structures.

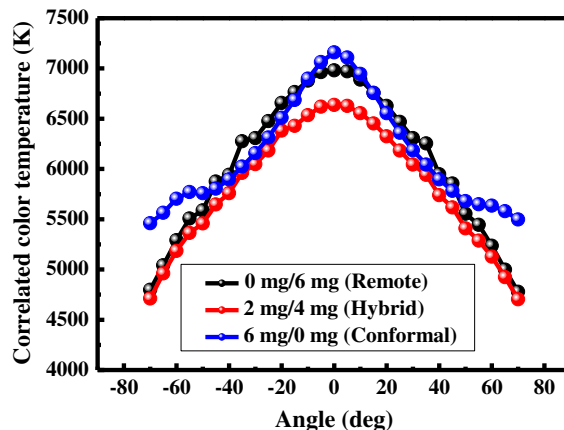
Sample	Remote	Conformal	Hybrid
Total phosphor amount at 5300 K	21.9 mg	25.8 mg	18.8 mg
Phosphor saved (%)	+16%	+37%	—

the total amount of phosphor in three white LED structures, which have the same CCT at almost 5300 K. The total amount of phosphor for the remote, conformal, and hybrid phosphor structures were 21.9, 25.8, and 18.8 mg, respectively, at the same CCT. In our experiment, to achieve the CCT we need, the amount of yellow-emitting YAG phosphor for remote and conformal phosphor structures was larger than that of the hybrid phosphor structure, which significantly increased the cost of high efficiency white LEDs. As shown in Table 1, the experimental results indicated that the phosphor saved in the hybrid phosphor structure amounted to 17% for the remote phosphor structure and 37% for the conformal phosphor structure at 5300 K. In order to clarify the CCT uniformity, the CCT deviations of the hybrid structure, conventional remote structure, and conformal phosphor structure were investigated. The angular CCT deviation curves from -70 to 70 deg are shown in Fig. 5. The CCT deviations were 1760, 2200, and 1630 K for the hybrid structure, remote structure, and conformal phosphor structure, respectively. Therefore, a better uniformity of angular-dependent CCT was obtained in the hybrid structure compared to the conventional remote phosphor structure.

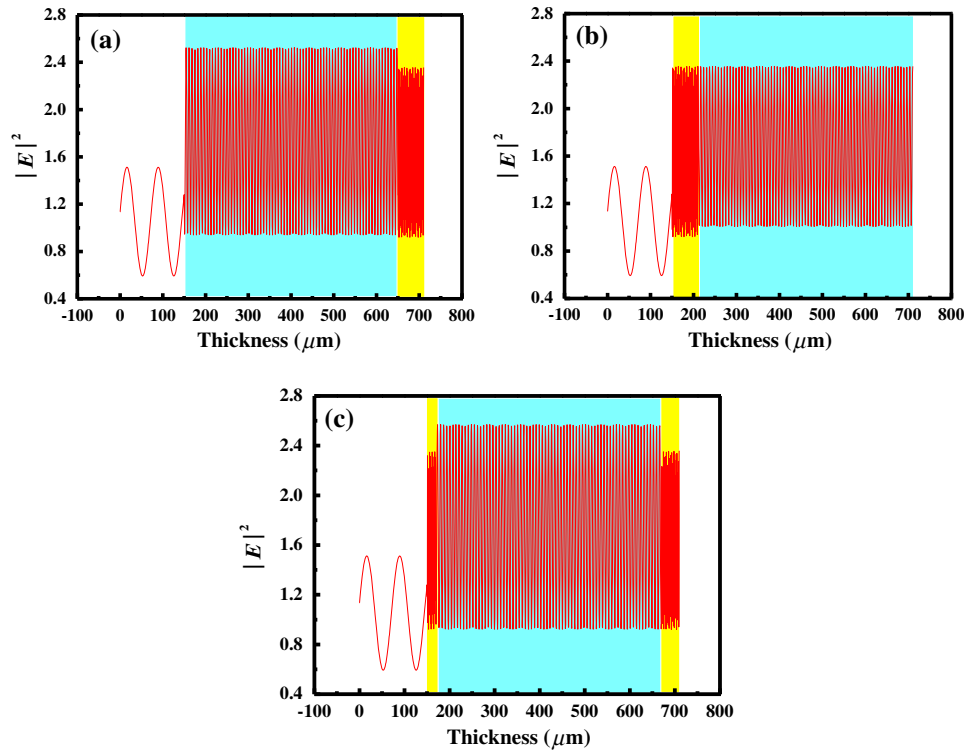
To understand the effect of blue photons coupling to the phosphor layer, a TFCalc32 simulation was employed in the experiment.<sup>29</sup> In the simulation of the hybrid structure, the lengths of the silicone layer, bottom phosphor layer, and top phosphor layer were approximately 500, 20, and 40 μm, respectively. Regarding the remote and conformal phosphor structures, the lengths of the silicone layer and phosphor layer were approximately 500 and 60 μm, respectively; 450-nm light was emitted incident to these layers by a GaN LED chip. Figure 6 shows the electric field intensity for the various thicknesses of remote, conformal, and hybrid phosphor structures. The electric field intensity in the hybrid structure was higher than that in the other two structures. Therefore, the advantage of the hybrid phosphor structure is that incident blue rays can be trapped in the silicone layer, increasing the absorption ability of the phosphor layer and allowing the transfer of more yellow rays compared with the other two structures.

The power intensity in phosphor layers of remote, conformal, and hybrid phosphor structures applied in white LEDs can be calculated as follows:

$$W = \frac{\int_{650 \mu\text{m}}^{710 \mu\text{m}} n_p^2 \times |E|^2 dT}{\left[ \int_0^{150 \mu\text{m}} n_{\text{GaN}}^2 \times |E|^2 dT + \int_{150 \mu\text{m}}^{650 \mu\text{m}} n_s^2 \times |E|^2 dT + \int_{650 \mu\text{m}}^{710 \mu\text{m}} n_p^2 \times |E|^2 dT \right]}, \quad (1)$$



**Fig. 5** The CCT deviations of the remote, conformal, and hybrid phosphor structures.



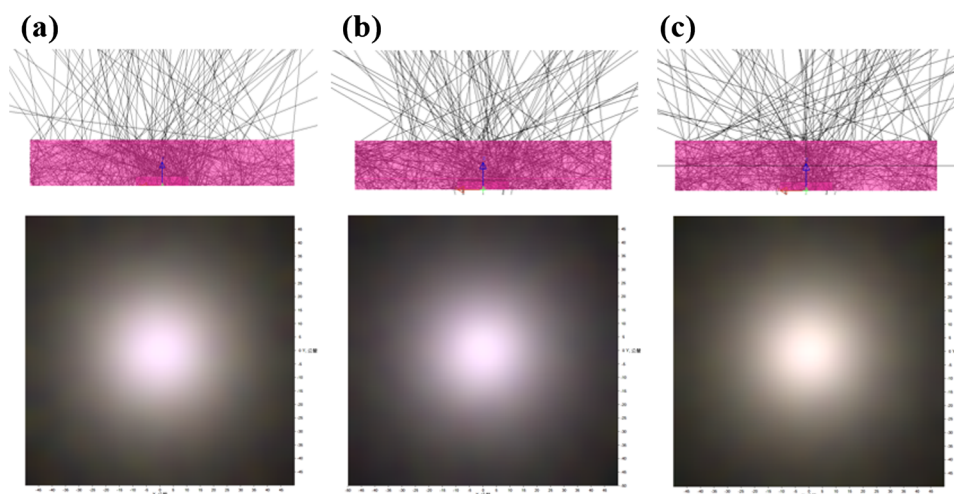
**Fig. 6** Thickness-dependent  $|E|^2$  of the (a) remote, (b) conformal, and (c) hybrid phosphor structures by TFCalc32 simulation.

$$W = \frac{\int_{150 \mu\text{m}}^{210 \mu\text{m}} n_p^2 \times |E|^2 dT}{\left[ \int_0^{150 \mu\text{m}} n_{\text{GaN}}^2 \times |E|^2 dT + \int_{150 \mu\text{m}}^{210 \mu\text{m}} n_p^2 \times |E|^2 dT + \int_{210 \mu\text{m}}^{710 \mu\text{m}} n_s^2 \times |E|^2 dT \right]}, \quad (2)$$

$$W = \frac{\int_{150 \mu\text{m}}^{170 \mu\text{m}} n_p^2 \times |E|^2 dT + \int_{670 \mu\text{m}}^{710 \mu\text{m}} n_p^2 \times |E|^2 dT}{\left[ \int_0^{150 \mu\text{m}} n_{\text{GaN}}^2 \times |E|^2 dT + \int_{150 \mu\text{m}}^{170 \mu\text{m}} n_p^2 \times |E|^2 dT + \int_{170 \mu\text{m}}^{670 \mu\text{m}} n_s^2 \times |E|^2 dT + \int_{670 \mu\text{m}}^{710 \mu\text{m}} n_p^2 \times |E|^2 dT \right]}, \quad (3)$$

where  $n_{\text{GaN}}$ ,  $n_s$ , and  $n_p$  are the refractive indices of GaN, silicone, and phosphor, and  $|E|^2$  is the electric field intensity. According to Eqs. (1), (2), and (3), the power intensities ratio  $W$  in the phosphor layers of the remote, conformal, and hybrid phosphor structures were 8.5%, 8.8%, and 10.1%, respectively, at a wavelength of 450 nm. The power intensity can be enhanced by 18%, which causes additional blue rays to be trapped in the silicone layer. In addition, the absorption probability of phosphor can be enhanced, enabling additional yellow rays to be produced through the recycling of photons.

Moreover, the LightTools simulation software based on the Monte-Carlo method was employed to simulate the ray tracing for the three structures.<sup>30</sup> In the simulation, the parameters of the refractive index in the phosphor, silicone, and LED chip were set to 1.6, 1.53, and 2.4, respectively. The average particle diameter and the concentration of phosphors were set to 13  $\mu\text{m}$  and 50%, respectively, which was uniformly distributed in the silicone binder. The phosphor absorbed blue light from the LED chips and emitted isotropic yellow light. The amount of light being absorbed and scattered by phosphor particles was simulated using Mie theory. Figure 7 shows that the capability to use the blue rays in the silicone layer was higher in the hybrid phosphor structure than in the other two structures, indicating that the utilization of blue rays and lumen flux increased. Moreover, the simulated luminous flux of remote, conformal, and hybrid phosphor structures were 120, 117, and 125 lumen, respectively. These results correspond with the aforementioned finding—the hybrid structure provides greater light output than conventional structures do.



**Fig. 7** The simulated cross-section light propagation of (a) remote, (b) conformal, and (c) hybrid phosphor structures and the corresponding far-field emission patterns.

## 4 Conclusion

In conclusion, the hybrid phosphor structure enhances the luminous efficiency of WLEDs; this enhancement was caused by the increased utilization of blue rays from the WLEDs. The results indicated that the luminous efficiency of the hybrid phosphor structure improved by 5.9% and 11.7% compared with the conventional remote and conformal phosphor structures, respectively. Moreover, the hybrid structure save more than 17% and 37% in phosphor usage compare to the remote and conformal structures at the same color temperature of around 5300 K. Finally, the TFCalc32 simulation revealed that the utilization of blue rays was higher in the hybrid phosphor structure than in the other structures, increasing the luminous efficiency.

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